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FINAL REPORT

DEVELOPMENT OF METHODOLOGIES FOR VESTIBULAR EXPERIMENTATION WITH MAN AND ANIMALS

APRIL 25, 1977

KRESGE HEARING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

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FINAL REPORT

DEVELOPMENT OF METHODOLOGIES FOR VESTIBULAR EXPERIMENTATION WITH MAN AND ANIMALS

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BY

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ABSTRACT

Work was completed on the design and construction of a motor driven platform which is capable of limited horizontal linear motion in one dimension. Included with the platform is a control system which allows translation velocity to be determined by computer input. The evential uses of the device are studies on the postural dynamics of standing human subjects. An optical measurment system has been developed to work in conjunction with the platform by sampling the position of body links and thus yielding the information necessary to quantify the subject responce to base of support translation.

A plan for the further development of the device is presented with plans for a series of experiments which will determine the responses of human subjects to a number of different stimuli.

Calculation on the possibilities for an animal centrifuge which will be usefull in the study of the otolith organs in space research are presented with discussion on the design of such a centrifuge.

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SUMMARY

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Two major areas of interest in the study of equilibrum are covered by this report. The first is our work on the development of a moving platform, a optical measurment system and analysis algorithms for evential application in a test procedure for human postural control. The second area is a study on the use of the centrifuge for otolith research in space.

Optical position Measurment System- The utalization of the Reticon scan cameras has been improved both mechanically and electronically. The cameras have been mounted on a single vertical stand which can be finely adjusted for proper vertical alignment. The mounting hardware allows the cameras to be positioned vertically with great ease thus allowing the operator to quickly change from one height to another to accommondate different subjects. Electronically the camera control systems have been reformated into a Tektronix Incorporated TM500 series module kit. The circuit works is it did at the onset of this contract but the 2 dimentional aspect of it has been removed.

Moving Platform Development.- The major portion of the platform construction has been completed and is in good working order. Work is still continuing on the reduction of noise which was identified as a problem early in the testing and on the proper development and placement of safty devices. Subject testing should begin under contract NAS 9-15244 as soon as the LSI-11 computer equipment arrives and is integrated with the platform electronics.

Subject Data Analysis- The techniques of analysis have been developed and are ready for commitment to software and verification with the platform and the position measurment system. The stumuli section of the software will make periodic stimuli available from the most simple and predicable. sinusoidal wave form to the complex psedorandom noise stimuli which can not be predicted by the subjects. Transient stimuli will also be available for the application of sudden movements of base of support with out warning. All of these techniques will be used in a systems identification approach to the postural control

system.

Centrifuge Systems- Some theoretical concepts of centrifuge design were discussed in relation to the development of a centrifuge which could be used in a weightless environment. The major goal was to discuss ways in which a centrifuge can be used to explore the region between zero and one unit of gravitational acceleration. It was assumed that a centrifuge could be built which has three degrees of freedom in its state of motion. That is, radial length, angular velocity and angle of the subject with respect to the radius. Using some or all of these parameters, 4 different techniques were explored for the delivery of time varing linear accelerations.

OPTICAL POSITION MEASUREMENT SYSTEM

The optical position measurement system was designed and built in its original form for the postural measurements required in a bedrest study conducted in part at the NASA-JSC neurophysiology laboratory (See Ref. 1). Initital experience with the system during this brief application led to a number of recommendations on how it could be improved for use in future experiments. If the possibility of field experiments is to be considered as well, then the optical measurement system must be very much more transportable than as first devised. One of the objectives of the current contract is to make the optical position measurement system more portable and integrate it more closely with the eventual complete dynamic postural analysis system which will be completed under NAS 9-15244. The experiences at NASA-JSC brought out a number of features which could be improved. The following is a list of four problems which were solved under this contract.

1. The camera mounting hardware which originally consisted of two photographic tripods was difficult to align and resulted in different scale factors for the two cameras. No simple method by which height could be measured and reproduced from session to session was provided.

2. The cameras were not synchronized together thus resulting in an inconvenience when viewing the video patterns of the two systems together on the same dual trace oscilloscope.

3. The packaging of the electronics was such that it could not be easily rack mounted as would be required in the final portable system.

4. The two dimensional provision which was originally designed into the system proved to be an unnecessary circuit complication.

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Camera Mounting System

These problems could be in part solved by a new camera mounting system. Such a mount was designed and built in our mechanical shop. The finished device incorporates the following important features:

1. Single post for both camera mounts- As shown in Figure 1, the cameras are coupled together mechanically such that when adjustments of alignment are made they can be made on both cameras simultaneously. There is no error due to horizontal displacement of the cameras with respect to each other because they are mounted one above the other.

2. Individual coarse and fine adjustment of height- The mount for each camera can be independently moved up or down on the single vertical post by hand. Fine adjustments are made by a rack and pinion arrangement on each mount. Both the coarse and the fine adjustments can be locked. The detail of this device is shown in Figure 2.

3. Leveling adjustment- The base has leveling screws built into it so that vertical alignment of the post can be achieved. To aid in this task, a leveling glass is incorporated into the base. Figure 3 shows the leveling screws and the leveling glass.

4. Portability- The vertical post is built in three sections which can be taken apart for storage or shipment.

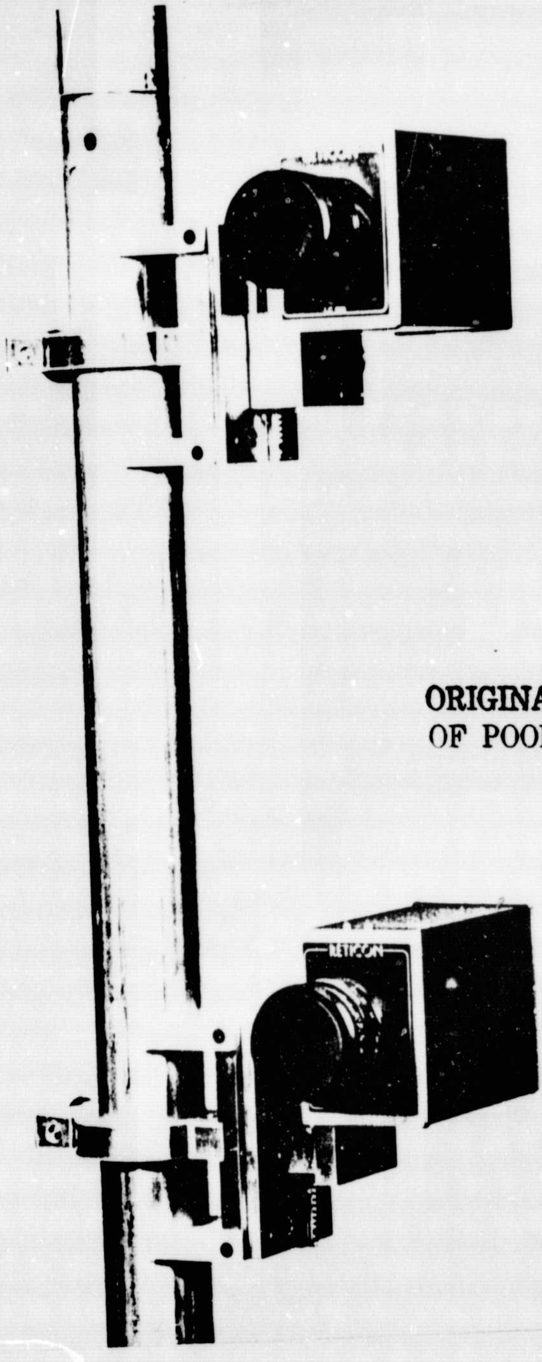

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Figure 1- The two Reticon line scan camera are shown mounted on the vertical post aligned and in position.

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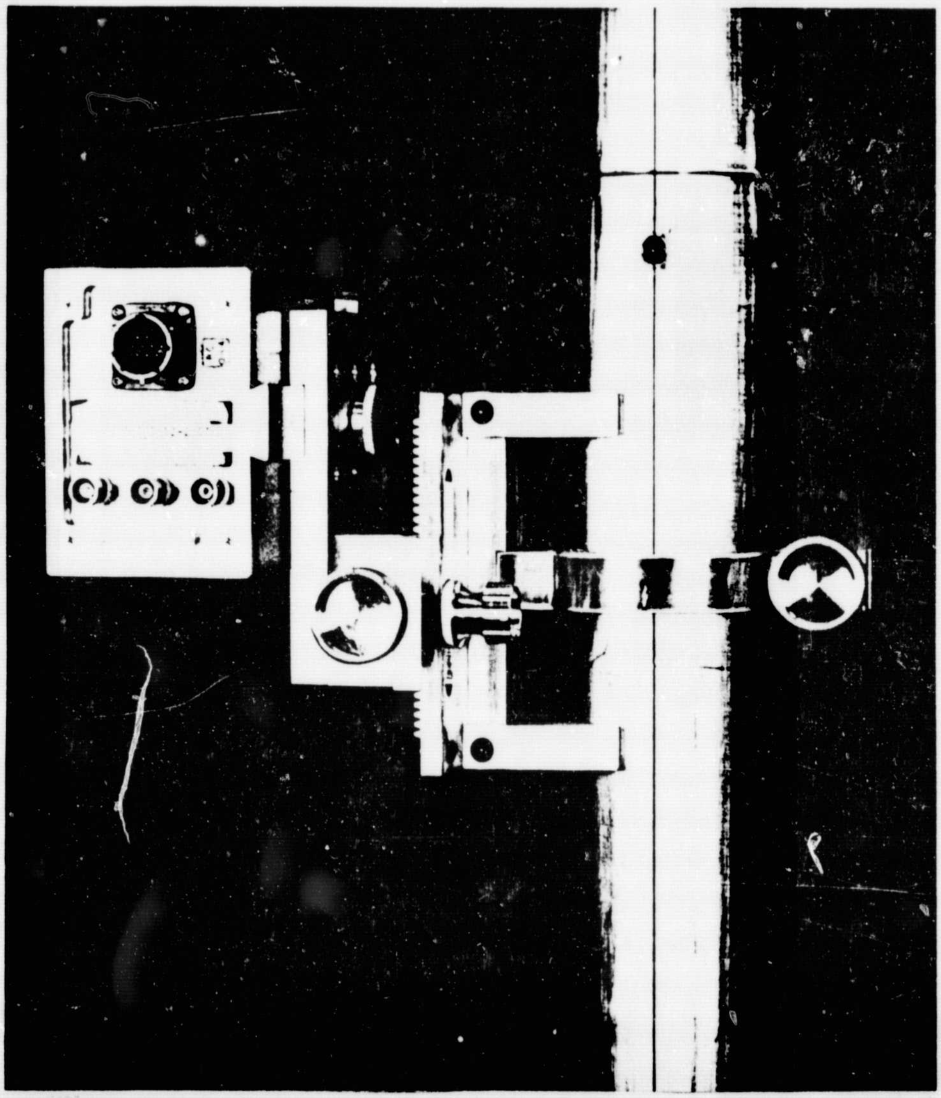

Figure 2- Detail of the mounting hardware shows course adjustment for position of the mount on the post and the fine adjustment of camera position with respect to course mounting position.

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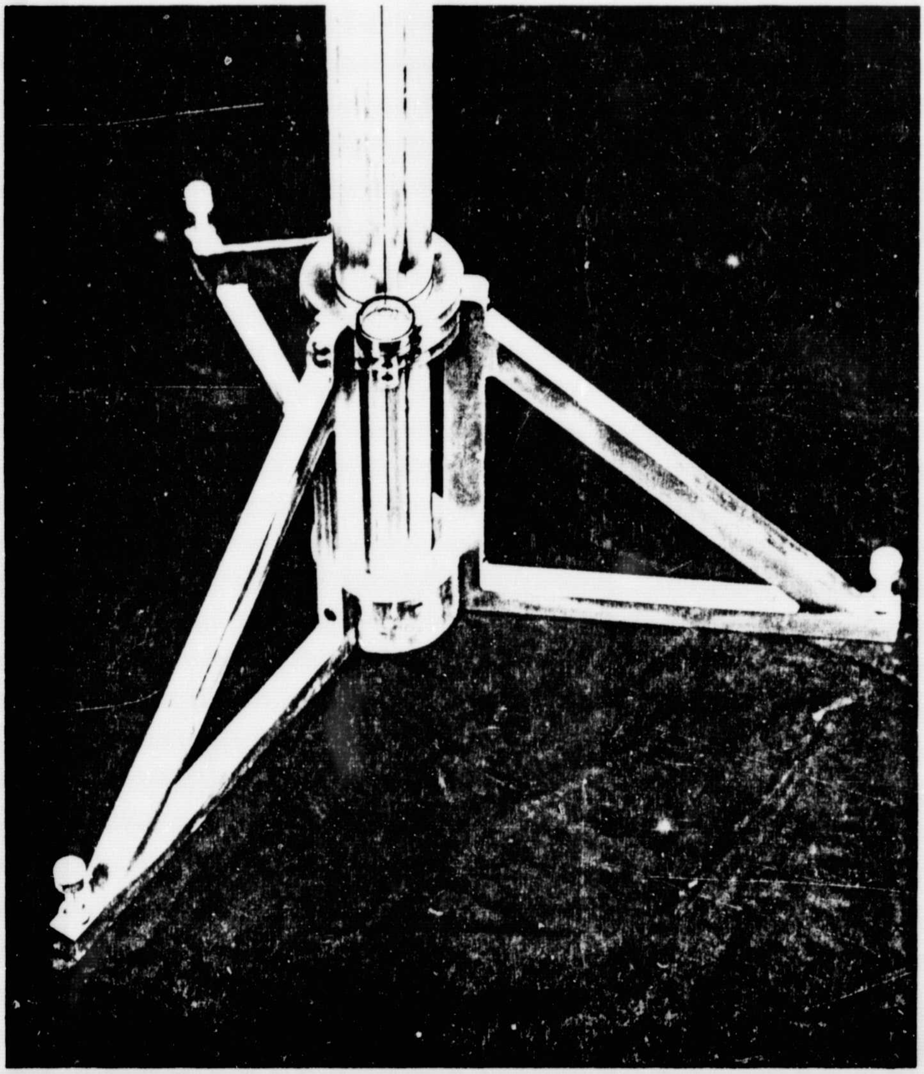

Figure 3- The camera mount base has built-in leveling screws with a sight glass for easy adjustment of proper vertical.

Camera Electronics Packaging

The changes in the electronics interface between the cameras and the recording system are primarily mechanical in nature and do not change the one-dimensional electronic operation of the devices. The Tectronix Inc. TM500 series TM506 power module and a double compartment plug-in kit were chosen for the packaging of the camera electronics. The original wire-wrap circuit boards built at NASA-JSC were remounted in the plug-in kit. Power to the circuitry is provided from the original power supply purchased for the unit. It is rack mounted above the TM506 power module and also contains 4 active low pass filters set to 50 Hz which are to be used as anti alias filters for computer sampling. The camera cables are mounted to the back of the power module through the module connectors provided with the kit. The receptacles for the circuit outputs were also mounted on the rear of the power module. The only change in the electronics was to eliminate the two-dimensional provision of the circuit. Camera interface circuit outputs can be monitored by a DM502 digital voltmeter also mounted in the TM506. The voltage measured by this device is directly proportional to the target position. As yet no provision has been added to the electronics for the direct digital readout of the position measurement pending final configuration of the complete dynamic posture analysis system. It is expected that the value of having the output in analog form will remain for some time and the D/A converters in the interface should therefore be preserved. To improve the quality of conversion back to digital form, the four low pass filters mentioned above were added to the system in anticipation of its connection to a digital computer through A/D converters.

MOVING PLATFORM DEVELOPMENT

By far the greatest resources of this contract have been expended on the development of the moving platform. This is justified by the fact that the flexibility of future test protocols hinges upon the versatility of the stimulus delivery system.

Specifications

After a study of requirements, we have settled upon the following specifications:

1. 24 inch total linear travel
2. 1 ft/sec maximum rate of linear translation
3. 3 Hz response at maximum velocity
4. 60 Hz - 115 volt power requirement
5. Primary control will be a voltage command from a function generator or computer

The first three specifications deal with performance characteristics and the last two relate to convenience of operation. Certain less hard specifications are:

1. low acoustic noise
2. low vibration noise
3. low mechanical backlash in the control
4. Safe for human subjects

These specifications are not quantified mathematically but are extremely important to the ultimate success of the project. The last one, of course, is a requirement of the project but also of our laboratory and the University of Michigan human use committee.

Construction

Although there would have been certain advantanges to a hydraulic drive system in terms of power and smoothness, we decided the cost, mechanical complications and possible lack of portability did not justify such a system. The configuration decided upon was a torque motor coupled to the platform by a 1/4 inch pitch lead

screw and a preloaded ball bearing nut. It was found that the Electrocraft Corporation of Hopkins, Minnesota had a line of torque motors, tachometers and matched power supplies which could meet all of the specifications outlined above. The torque motor is of the permanent magnet D.C. type (Electrocraft E703-01) and is driven by a servo amplifier (Electrocraft 6200AP) which receives velocity commands from an external source. Closed loop control is maintained through a tachometer (Electrocraft M110). The stall torque of the motor is 410 oz.in. and it can operate at a maximum angular speed of 3000 RPM. The motor is shown mounted in Figure 4. Although not part of the regular control system, position feedback may be obtained from a potentiometer (shown in Figure 5) which we have geared to the platform. The platform itself is two feet square, a sufficient size upon which a man can stand erect with a comfortable stance. It is mounted on two parallel stainless steel rails with ball bushings which allow it to slide two feet from stop to stop. The platform with its drive mechanism is enclosed in a 2'x5' aluminum box, one foot high. Figure 6 shows the overall view of the platform.

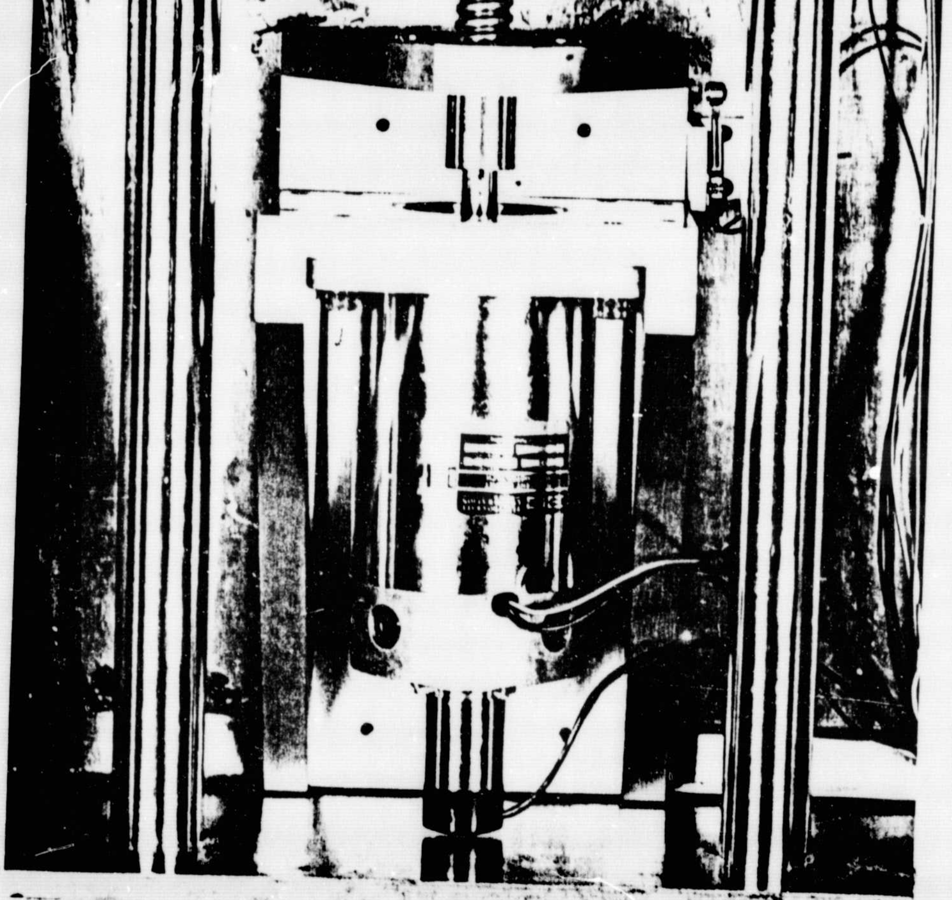

Figure 4- The motor and tachometer are shown fitted to the lead screw. On each side of the motor are the stainless steel rods which support the platform. Note the limit switch mounted beside the rod on the right.

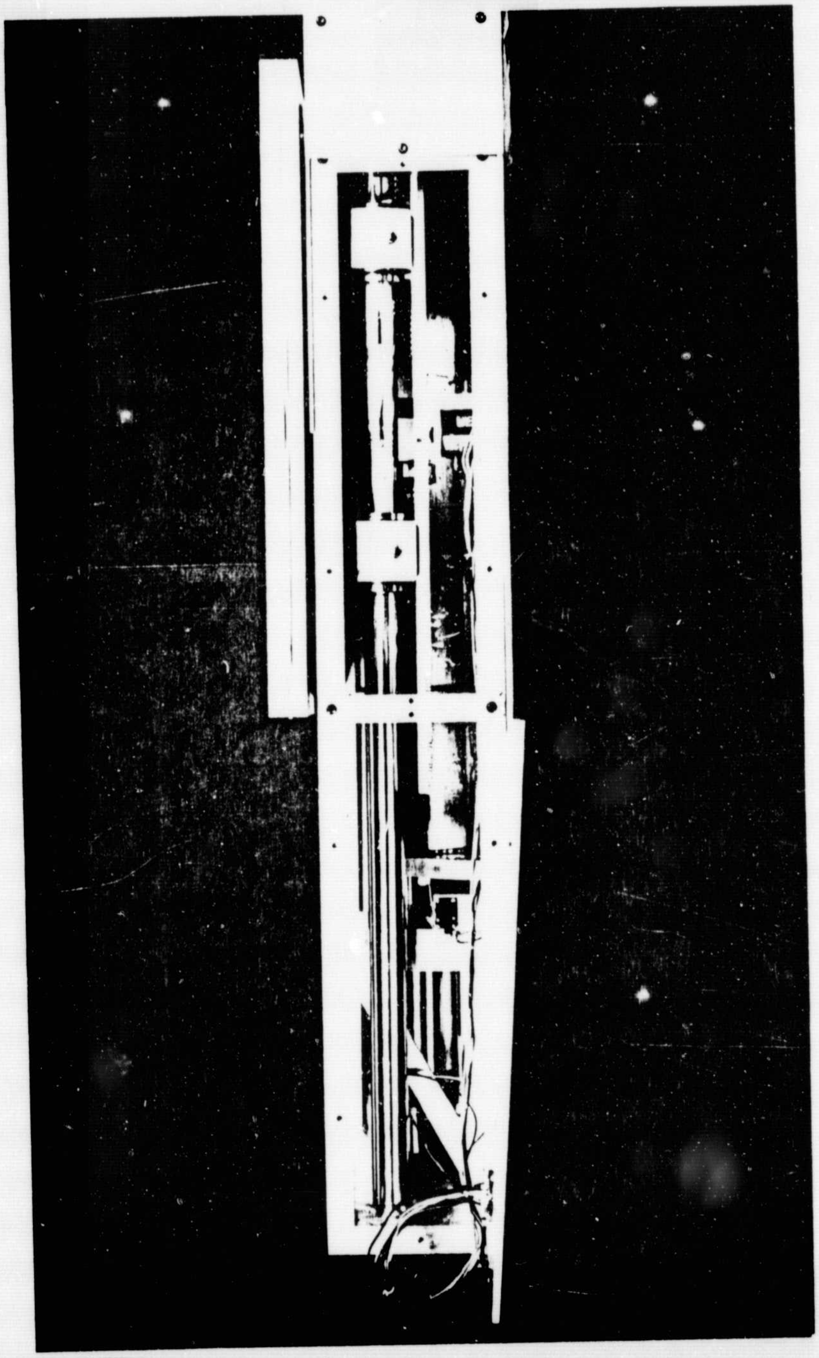

Figure 5- A side view of the open platform showing the ball bearing bushings riding the stainless steel rails. Attached to the bushings is the rack which drives the potentiometer.

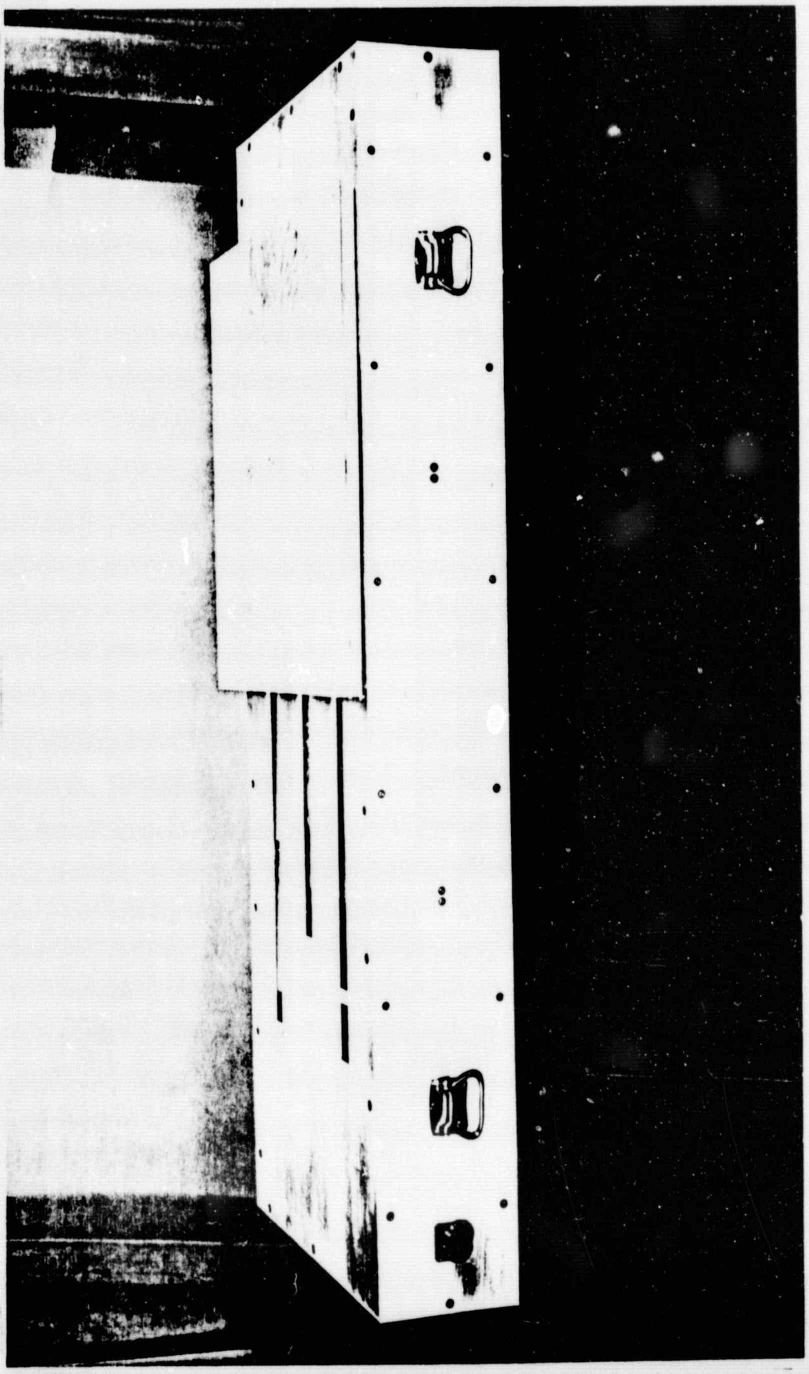

Figure 6- An over all view of the complete device minus the safty covers and rails.

Safety Provisions

The power of the system is such that physical injury to subjects could easily occur if the platform's force was applied so as to squeeze or pinch. There are, therefore, provisions to cover all moving parts of the device and to provide adequate safety switches to cut off power in emergencies. The exact configuration of safety switches has not been determined but they will be arranged such that they can be applied by either the subject or the operator. The most probable locations are foot operated switches located in the moving platform or switches on hand rails mounted near the platform.

Testing to Date

The basic electrical and mechanical components of the system are complete to the point where testing of platform performance can begin. The servo amplifier was adjusted for the proper gain and compensation characteristics according to the instructions delivered with it. Simple sine and square wave tests were performed to assure ourselves that the system at least responded correctly in principle. The system was driven by both sine and square waves of maximum velocity from .5 Hz to 5.0 Hz without noticeable problems. Lower frequency tests were conducted at lower velocity amplitudes to avoid excursions beyond the 2 foot peak to peak limit of motion. Detailed frequency analysis of the system will be completed once the platform control can be joined to the computer system sometime in the summer of 1977.

A problem which occurred when the first tests were conducted both with the platform operating without load and with one of the laboratory personel riding it was that of excessive acoustical noise and vibration transmitted through the moving platform. In our efforts to create a low friction mechanism, we used ball bushings throughout. The sound they produce coupled with the fact that the sides of the box are made of aluminum plate yields a poor acoustic situation. We have attacked the problem in a number of ways:

1. A new set of ball bushings was ordered which use teflon balls in place of the steel. These new

bearings may not have the long life characteristics of steel but will be much quieter at no sacrifice of ease of motion.

2. The damping characteristics of the platform surface have been improved by laminating a lead impregnated plastic and a plywood sheet to it, thus mechanically isolating the platform from the leadscrew and the ball bushings. This has already improved the system considerably. Sound absorbing foam will be placed on the inside surface of all aluminum plates to reduce the amount of internal noise which is available for excitation of the plates.

3. All tests so far have been conducted by placing the box on the hard floor directly. Future tests and applications will be made with the box on a laminated material similar to that mentioned in item 1 between the aluminum box and the floor.

Drive Algorithms

Much thought has been given to both the types of voltage commands which will be delivered to the velocity control of the platform and to the types of processing which will be done on the resulting body measurement data. The goals for these signals are to provide a sufficient range of challenge for the subject so that he must apply all his capacity to maintain postural stability.

Easily anticipated sinusoidal signals of various frequencies will be used to test control of posture when all muscle forces can be preprogrammed. More complex but still periodic signals, made up of a number of different harmonically related sinusoidal components, will be used to subject the rider to a smoothly delivered yet difficult to anticipate motion. By adding one component of the complex wave form at a time into the pattern of motion, it will be possible to cover the well anticipated to almost random in a number of discrete steps. The most complex wave form will have 7 components. We have spent considerable thought in the development of the method by which the phase of the components can be determined. For the final waveform to be pseudorandom in nature, the phases must be random. The constraint that the waveform must begin at zero velocity forces the last phase to be

calculated on the basis of the other components. If this cannot be done, the whole group must be recalculated. It is possible by selecting from a number of waveforms constructed as above, to choose one which has a minimum of excursion with a maximum amount of energy in each component.

The last type of stimulus is transient in nature. In systems analysis, mathematical studies may be carried out using the ultimate of transients- the impulse function. As with all physical systems, biological systems can only be described by linear techniques over a limited range of input values. The impulse, as attractive as it appears mathematically can not be used physically. If the energy contained in an impulse function is spread out in time, then the maximum amplitude can be reduced without decreasing the total energy, or changing the distribution of energy over frequency. There is a class of all-pass digital filters which have the characteristic of accomplishing this task (See Ref. 1). When a digital impulse is applied to this digital filter, the output can be used as the transient input to the table velocity control. The result is a minimum excursion for a maximum amount of energy.

SUBJECT DATA ANALYSIS

All of the signals proposed for application to the platform control system are rich enough in spectral content to be adaptable to perform systems analysis on the postural control mechanisms of human subjects. It will therefore be possible using frequency domain techniques to describe the response of the postural control system to the three different types of stimulation. Data analysis techniques and subject analysis procedures will be developed in four phases:

Phase I: Experiments describing the stimulation/measurement system performance

Calibration of the platform control system will proceed by determining the linear range of platform motions. Distortion criteria will be established using a 200 lb mass as a load on the platform, and driving the platform to the limits of its performance. Sinusoidal stimuli along with steps of input velocity will provide data to specify the possible ranges of stimulation parameters for each of the impulsive, sinusoidal, and pseudorandom noise waveforms.

Especially during the low frequency, high amplitude platform movements it will be necessary to optimize camera focal length to measure the system resolution in terms of linear subject displacement perpendicular to the camera focal axis. This process will not require experimental data, but can be accomplished in a straightforward manner once the maximum link displacement is known.

The proper functioning of the safety railing and the heel-toe foot switches (See Ref. 2) must be assured. This equipment will be tested on lab personnel before subjects are exposed to tests on the platform.

Final tests of system performance will be in the software area. The subroutines for FFTs, autocorrelation, and crosscorrelation will need to be tried on standard test data which will yield known results. The assembly code D/A and A/D control routines will need verification, also. Test data will also be run through the transfer function extraction routines to ensure correct results. Once the computer software is ready, the

platform is calibrated, and the cameras properly positioned, tests on human experiments can proceed.

Phase II: Experiments on otoneurologically normal subjects to determine the inter- and intrasubject variabilities in response to the respective types of controlled postural disturbances

First the control situation will be discussed. The subject will be asked to wear tennis shoes, in an effort to standardize torque generating capabilities around the ankle joints among the subjects. The platform will be shown to the subject, and its safety devices (railing and foot switches) will be explained. The subject will watch the experimenter operate the platform, so he understands his task. He will then be asked to assume stance on the platform with his heels together, toes out at 45 degrees, with a hand on the railing. He will next be fitted with earplugs and a blindfold, and once the blindfold is in place he will be asked to assume a relaxed, loose posture with his arms folded gently across his chest, his head facing straight ahead in the direction of platform motion. From this point the experiment can proceed, with no trial period requiring more than five minutes of stance. The subject will be instructed to stop platform motion if he feels the possibility of falling.

The line scan cameras will be configured to record AP oscillations of two link silhouettes simultaneously in the same vertical plane. The heights of the cameras delineating each subject's body links will be recorded for later normalization of transfer function characteristics. A decision will have to be reached about camera placement on the tripod in relation to the body link being monitored. Mathematical formulations of the errors produced by just tracing displacement along a horizontal scan when the link actually moves in a quasi-arc will have to be derived from some preliminary investigations on lab personnel. If the errors are large, a FORTRAN routine could conceivably correct for them, but it is anticipated that this will not be necessary. The subject's weight and height will also be recorded.

Moving now to experimental situations, the linear range relating input and output amplitude will be determined at different frequencies of both sinusoidal and pseudorandom noise platform

motions for each subject. This range will be described at each of four camera heights: the knees, the waist, the shoulders, and the head. For all of this incoming data, gain and phase information at selected frequencies and amplitudes will be calculated by the software package. At the same time data from the different links will be crosscorrelated with the records of platform position and adjacent link position.

Repeat measurements will be performed at different times of the day (morning, afternoon, evening) to assess the sensitivity of body link oscillation dynamics to diurnal rhythms. Repeat measurements on the same subject at the same time on different days will provide data for the analysis of intrasubject repeatability. Data variability will be expressed in terms of twice the standard error of the mean.

The crosscorrelation data will require processing to locate the shift value and amplitude of the peak(s) in the function. Once these parameters are determined, all of the frequency response gain and phase information, as well as the crosscorrelation data, will be ready for statistical treatment. The end result will be a description of both intra- and intersubject response variability.

At this stage of experimentation a decision can be reached about the usefulness of moving the cameras to all four positions. If the crosscorrelation data indicates that two camera-monitored links consistently yield the largest phase disparity, the need for recording data at all link levels evaporates. The obvious advantage of this result would be the halving of testing time and the amount of data to be stored.

Phase III: System identification

No new experiments are required in this phase. Data from Phase II will be used to plot average transfer functions of the normal subjects at either all four camera heights, or the two camera heights selected. This will be done for each dynamic input stimulus, and from these plots a mathematical formulation of the transfer characteristics will be derived analytically.

Phase IV: Effects of altering sensory feedback on dynamic response characteristics

The first experiment in this phase will be done with eyes open and fixated on a point straight ahead in the visual field. The average transfer functions will be compared with those obtained in the blindfolded situation. This experiment will indicate the effects of visual fixation on dynamic body sway response.

The next experiment is aimed at altering the vestibular input to the postural control system. While blindfolded, the subject will be asked to maintain his head at 90 degrees to straight ahead, both head left and head right. The average transfer function responses will be compared with the eyes closed, head straight situation. The symmetry of the head left versus the head right response will also be investigated on an intrasubject basis.

The last two experiments both involve proprioception. In one case a foam rubber pad will be placed on the platform under the subject's feet, changing both the proprioceptive and the exteroceptive feedbacks. The average transfer functions will be compared to those of the control situation. The final experiment will be an attempt to phase-lock different links with the platform while the subject responds to an impulse or a step input platform motion. This phase-locking should remove much of the proprioceptive feedback from the link used for feedback control down to the platform, if sway approximates inverted pendulum motion. Preliminary experiments will be needed to ascertain that enough movement is delivered to the links above the phase-locked link to provide a measurable response in these links. Allowance for the time course of the initial proprioceptive response to platform motion will have to be made before the phase locking is considered to effectively remove some proprioceptive cues.

A VERSATILE CENTRIFUGE SYSTEM FOR VESTIBULAR RESEARCH IN SPACE

Introduction

The sustained periods of weightlessness which are to be obtained in the Shuttle space Laboratory will afford an opertunity to accomplish a number of unique physiological experiments. One of the more interesting possibilities will be the exploration of the otoloth transducer function for acceleration in the range between zero and one G. This section of our report is an investigation into the centrifuge as the device-of-choice for the delivery of fractional G acceleration stimuli. It will be shown that the centrifuge has the potential to deliver stimuli useful in both time and frequency domaine analysis. It will be assumed that the centrifuge device has control systems which will allow not only programming of the angular velocity (W) but also the radius (R) and the subject angle (AL) with respect to the rotating reference. Some details are given which serve to illustrate how these control systems interact to porduce different stimuli but the analysis is by no means complete at this point-in-time.

Otolith Research in Weightlessness-

Research will continue using ground based systems to explore the transducer function and the frequency response of the otolith organs. No matter how detailed these studies become, the description of otolith function will not be complete until the fractional G region of stimulation has been explored. Extended periods of weightlessness can be achieved by use of the orbiting spacecraft. This in itself provides only one point in the region of interest. Methods are needed which can bias the stimulation system used in space at points other than zero G. The centrifuge can be used to do this but its use for dynamic situations is complicated by the mechanics of angular motion and requires very precise control. Several techniques are outlined below which can provide a variety of stimulus conditions for the study of the otolith system and the control system which depends upon it. We will start with a brief review of the equations which govern centrifuge operation.

Basic Physics of the Centrifuge-

The discussion which follows assumes that the centrifuge is constructed in such a way that the radius, the angular velocity, and the angle of the subject with respect to the radius arm are controllable. Figure 7 shows the conventions which will be used in the mathematical description of the mechanics. For further details on mathematical conventions as applied to the centrifuge, (See Ref. 3).

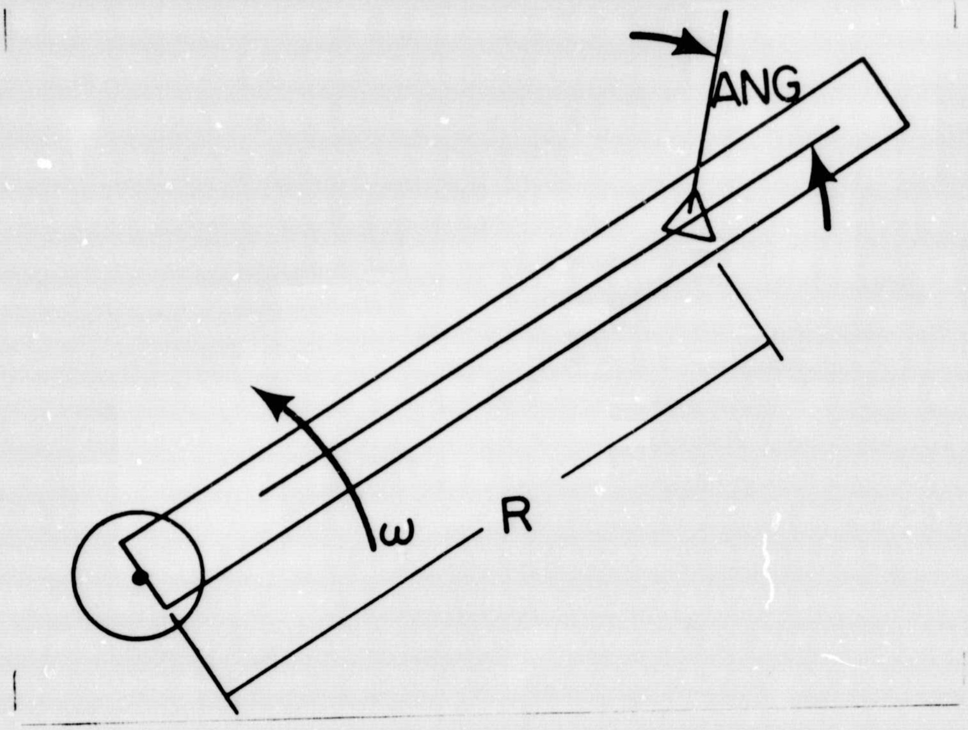

Figure 7- The three controlable parameters of the centrifuge are the radius, the angular velocity and the angle of the subject with respect to the radius.

For a fixed radius centrifuge operating at a constant angular velocity, only these two parameters are factors which determine the linear acceleration experienced by the subject. The radial linear acceleration is:

A(rad)=W*W*R (1)

where:
W= angular velocity
R= Radius
A(rad)=Acceleration directed to the

center of rotation

The angular velocity is the same for all points on the centrifuge. The force needed to restrain the subject to his position on the centrifuge radius is equal to the linear acceleration times the mass of the subject or:

F=M*A(rad)=W*W*M*R (2)

Once the magnitude of linear acceleration has been decided upon, equation 1 gives the trade off between angular velocity and radius. Figure 8 shows lines of constant A(rad) on a R.P.M. vs. radius plane.

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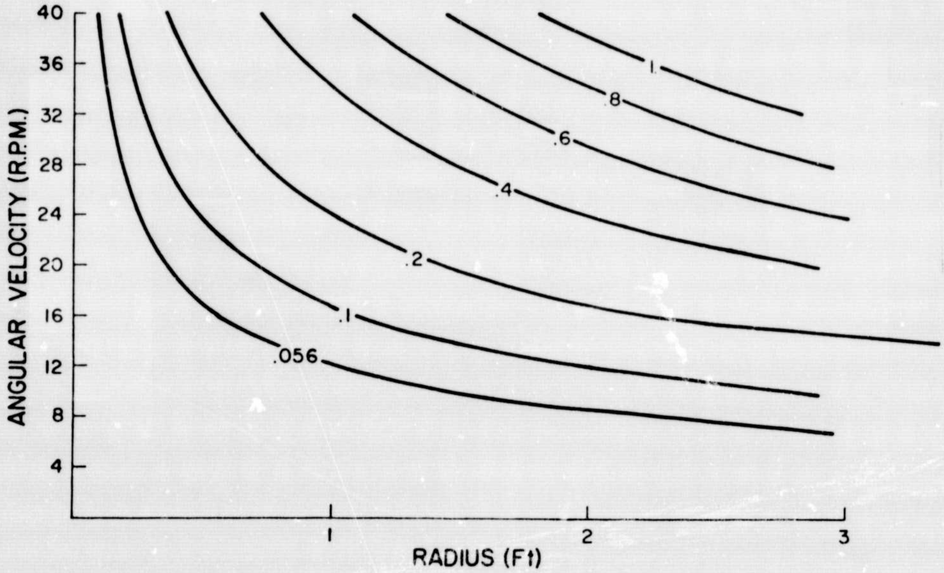

Figure 8- Trajectories of angular frequency vs. radius for a number of constant accelerations.

Aside from the normal component of linear acceleration which arises from the centrifugal acceleration there are three other components which arise when changes are made in angular velocity or radial length.

1. A tangential component of the linear acceleration will be generated when the centrifuge undergoes an angular acceleration. The magnitude of this component is:

A(tan)= AL*R (3)

Where:

AL= Angular acceleration
R=Radius
A(tan)=Tangential linear acceleration

2. A radial acceleration is produced when the radius has a non-zero second derivative. Its magnitude depends solely upon the value of the second derivative.

A(rad)=-R'' (4)

Where:

R''= linear acceleration along the radius

3. A tangential component called the Coriolis acceleration is generated when the radius changes during rotation. The magnitude of this component is:

A(tan)= 2*W*R' (5)

Where:

W= Angular velocity
R'= Linear velocity

A summary of the components which make up the total acceleration a subject could be subjected to is given by:

A(tan)= R*W' + 2*W*R' and (6)
A(rad)+ W*W*R - R'' (7)

The resultant value of linear acceleration will be:

ABS(A)= [A(tan)**2 + A(rad)**2]**.5 (8)

at an angle of:

Ang= ATAN(A(tan)/A(rad)) (9)

It is evident that while the centrifuge is changing either its angular velocity or its radius, the animal subject will be subjected to rather complex changes in acceleration vector not only in magnitude but also in angle. As an example, when the centrifuge starts from standstill and proceeds to a terminal rate, the linear acceleration vector is first totally tangential and ends up being totally radial.

Methods of Obtaining a Non-Rotating Stimulus Vector-

The capability of a centrifuge device to produce constant linear acceleration makes it a good tool for studying steady state conditions. When the experimental objective involves using an acceleration vector which is changing with time, the usefulness of a centrifuge begins to break down. If, however, one is willing to accept angular accelerations and fairly complex control systems which control the centrifuge speed, the radius of the arm, and the subject orientation angle with respect to the radius vector, then there are several possibilities for extending the usefulness of a centrifuge. There are three techniques which can be used to produce time varying acceleration vectors which do not rotate with respect to the subject. These techniques are outlined briefly below:

1. Constant Radius with change of W- Subject will have to align to the resultant of the normal acceleration due to rotational velocity and the tangential component due to angular acceleration.

2. Constant W with change of radius- The subject must be aligned with the normal component due to rotational velocity and the tangential component due to coriolis.

3. Change of both W and radius- If a proper choice of combined W and radius changes is made, no net tangential component will result.

Each of the three techniques listed above offer their own advantages. It depends upon the conditions which one should be used for a given experiment. A design example will be worked out below for each of the three techniques.

Constant Radius System-

This system depends only on changes in angular velocity needed to change the linear acceleration vector from one value to another. Since angular acceleration are required, the resulting tangential component must be compensated for by a rotation of the subject with respect to

the table frame of reference. One unique feature of this system is that a zero linear acceleration can be a starting point or an end point of a maneuver. Also in the system, step changes in linear acceleration may be obtained.

The equations of motion for this system can be obtained form equations 5, 7, and 8. The magnitude of the linear acceleration vector is:

ABS(A)=R*[AL*AL + W*W]**.5 (10)

Where:
R=Constant Radius
W= Angular Velocity
AL= Angular Acceleration

Solving for the angular acceleration which is required for a given ABS(A) we have:

A=[(ABS(A)**2/R*R) - W**4]**.5 (11)

If equation 11 were used as the control signal to the centrifuge control, the centrifuge system would go from a standing start to maximum R.P.M. as shown in Figure 9.

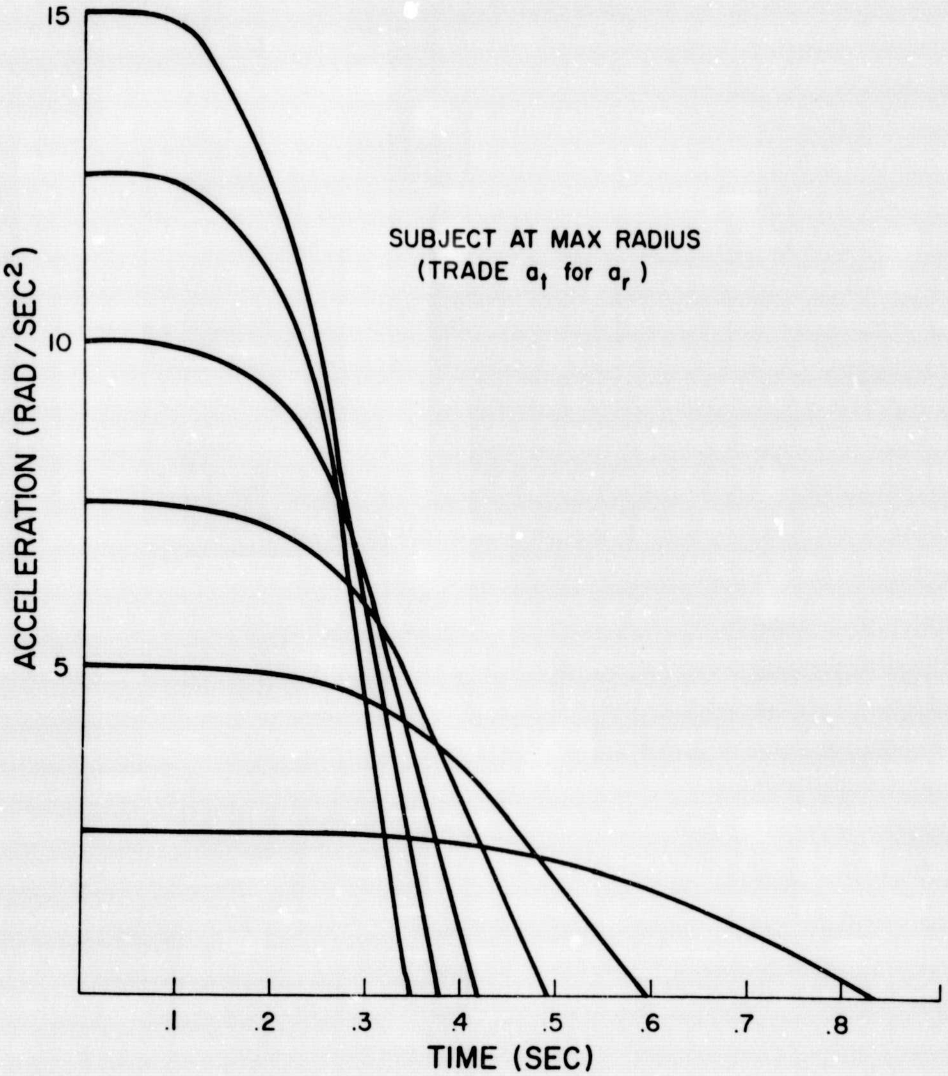

Figure 9- For the constant radius system, the angular acceleration of the arm is shown as a function of time for a family of different steps of angular velocity from zero.

It should be noted that the only normalization possible is to define as normalized acceleration. The behavior of the system is highly non-linear and would require careful control system design to assure stability. The higher the terminal angular velocity, the shorter the time required to achieve it. As an illustration of the time course of the various parameters, a detailed graph of the ABS(A)/R = 7.5 case is presented in Figure 10.

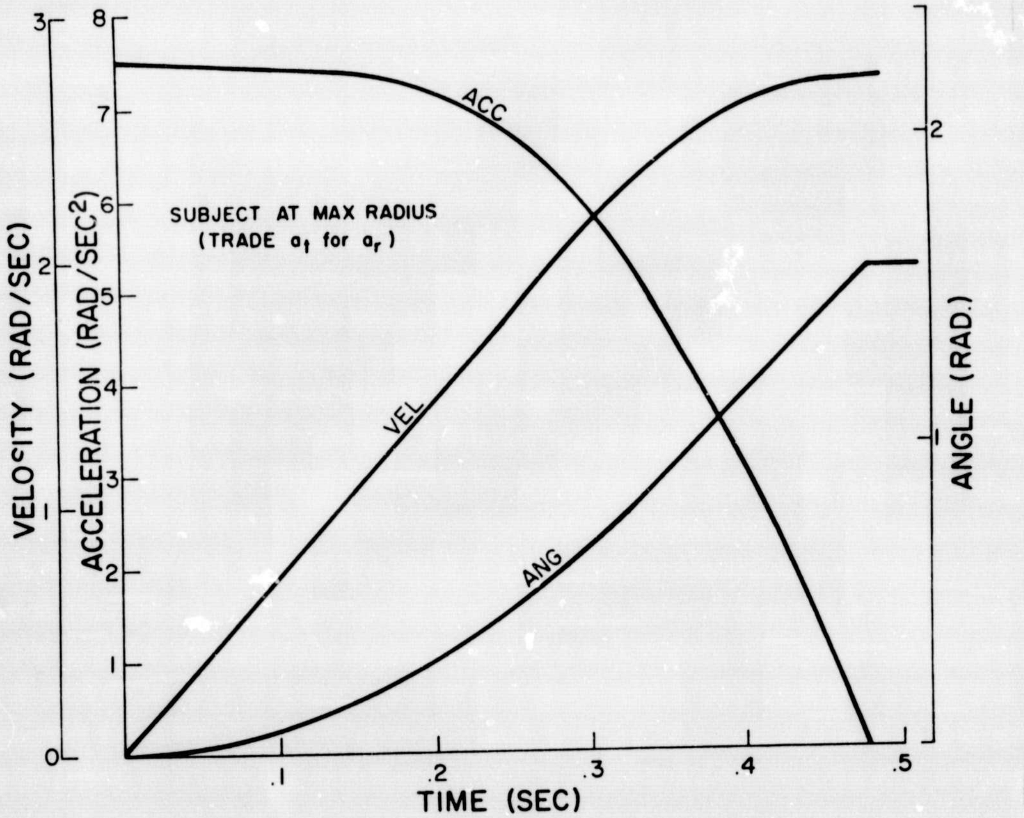

Figure 10- A particular case of step acceleration from zero to 7.5 is shown for the constant radius system. Also shown is the subject angle with respect to the arm which is needed for constant angle of acceleration with respect to the subject.

The angular acceleration is as shown in Figure 9, angular velocity is the integral of the acceleration and the required subject angle with respect to the centrifuge is derived from equation 9.

ANG(A)=ATAN(AL/W*W) (12)

An interesting feature of the curve is that it shows a near step change in angular velocity of the subject on the table. This could cause serious problems in control and stability of the subject on the platform.

An example of a more moderate transition which could be chosen for maneuvers between conditions is given below in equation 13.

X=(1/16)[8*U1-9*U2+U3] (13)

Where:

U1=X1+X0
U2=(X1-X0)*COS(B)
U3=(X1-X0)*COS(3*B)
X1=terminal value of X
X0=initial value of X
B=PI*t/T
T= Total time of movement

This equation has the feature of having very gentle starting and terminal conditions.

Constant Angular Velocity System

As shown in equation 1, the linear acceleration for a centrifuge is a function of the radius (R) as well as angular velocity (W). During change in the R the second derivative of R with respect to time causes an additiosl normal component and the first deviation contributes to a tangential component. The magnitude of the linear acceleration is therefore:

ABS(A)=(W*W*R-R"*R")+(2*W*R')**2)**.5 (14)

Solving for R, we have:

R"=W*W*R-[ABS(A)**2 - (2*WR')**2]**.5 (15)

This equation points out that there are restrictions on how ABS(A) can be changed. The most important restriction is that monotonic changes in ABS(A) can not be made in either direction. This mathematical complication coupled with the fact that R'' would be difficult to control directly makes equation 15 a unsuitable control equation. The approach taken for illustration will be to apply equation 13 as a direct control of R and adjust it such that the degree to which it is non-monotonic does not lead to rapid changes in the effective angle due to coriolis acceleration or a change of signs in the normal component. One normalized example of the strategy is shown in Figure 11.

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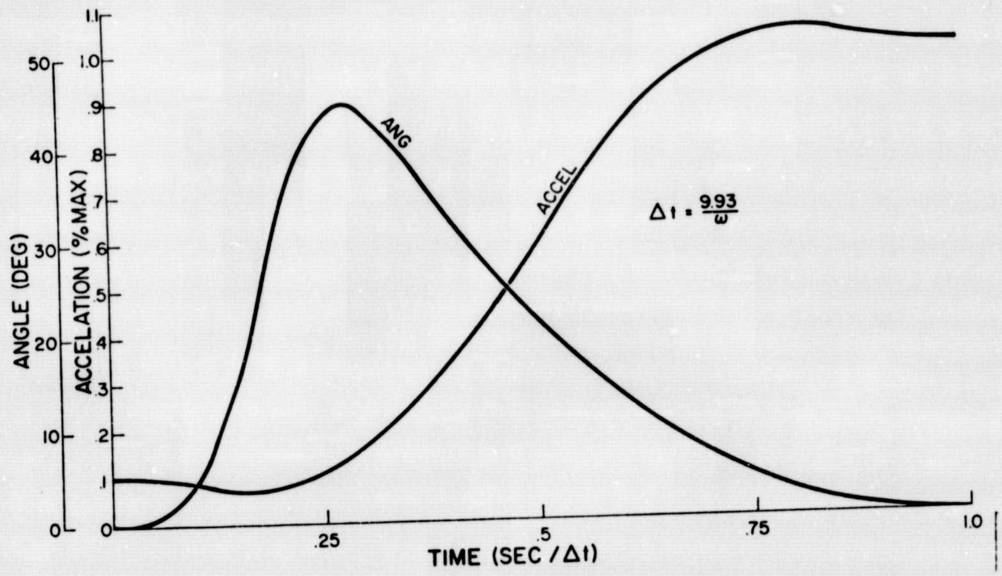

Figure 11- When a non zero rise time of acceleration can be tolerated for the constant radius system, the movement of the subject with respect to the arm can be more gentle.

The acceleration starts at 10% of its final value and has a rise time equal to 9.93/W seconds. The acceleration dips slightly blow 10% of the final value at first and over shoots the final value before settling. The subject angle with respect to the centrifuge arm must be charged as shown to compensate for the coriolis acceleration. It appears that no serious control problems would arise from this type of operation. Using the normalized curve of Figure 11, Figure 12 shows the implication of this type of maneuver for a family of different maximum arm lengths.

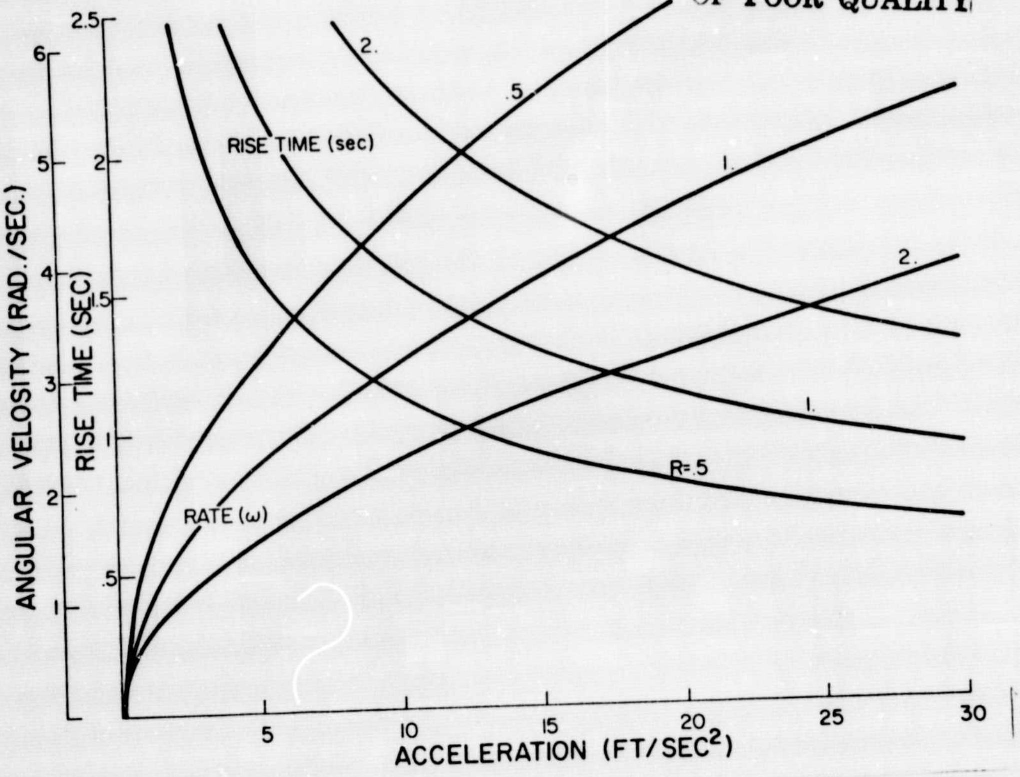

Figure 12- For different constant arm lengths, families terminal angular velocities and risetimes are shown.

Constant Angular Position Systems

It can easily be shown from Equation 5 that the total tangential component of the linear acceleration will be zero if the product of the radius squared and the angular velocity for the centrifuge is maintained at a constant value:

(16)

R*R*W=K

Using this information, a diffenential equation can be derived from Equation 7 which could serve as a control equation for the radius (R):

(17)

A(rad)= K*K/R**3 - R''

Although this control equation can be used to generate near perfect steps in linear acceleration, radius and angular velocity are

excited into an oscillation which contines undamped. Further, if additional maneuvers are executed without regard to the state of the device, the system can be excited into a higher level of activity. If this type of operation is to be attempted, great care must be taken to choose times for step changes which will result in a lower level of activity for the system. No attempt will be made here to analyze the conditions under which G load should be changed, but this problem should be carefully considered before use of this system of control.

Figure 13 illustrates two conditions of oscillation for the control system. One results from a transition from .1 G to .3 G and the other results from a .1 G to .5 G transition.

These illustrations serve to demonstrate that both the amplitude and period of the oscillation are dependent upon both the beginning and the end values of acceleration.

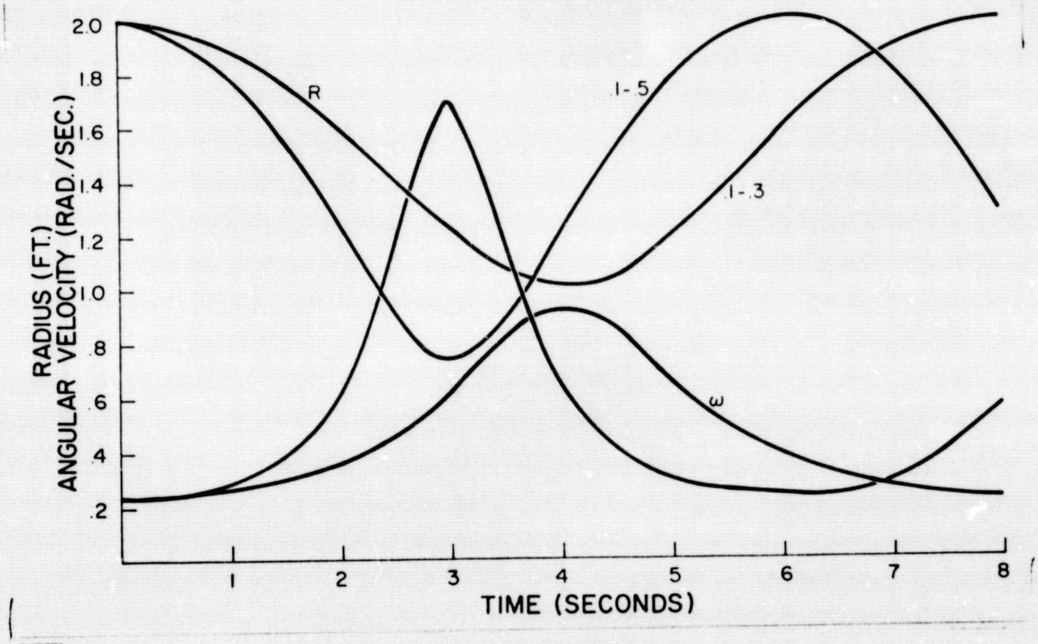

Figure 13- Two transitions from .1G are illustrated for the constant angular position system. Each transition results in a sustained oscillation of both angular velocity and arm length.

This system could be useful for sinusoidal stimulation, but a detailed analysis is needed to determine the admissible operating ranges. As above, great care should be taken to determine conditions which will not drive the system into excessively high levels of excitation.

It is evident that the harmonic content of the oscillation is considerable particularly for the higher amplitudes. Despite the distortion, these oscillations provide an excellent opportunity to determine the dependence of semicircular canal response upon G load in the fractional G range. The subject can also be counter rotated during this type of stimulation to produce net zero angular acceleration with a swing linear acceleration vector. The two stimulus conditions proposed above are unique and would be an excellent means for decoupling the angular acceleration effects and the swinging linear acceleration vector effects in the study of postural control mechanisms.

Zero Angular Velocity System-

For the condition where short transients or small sinusoidal variations about zero linear accelerations are required, the centrifuge can be operated without rotation simply as a linear accelerator by using only the control system which operates on the radial length.

Conclusions-

Depending on the size and power capability, a centrifuge with angular rate control, radial length control, and subject angle control can deliver the necessary stimuli to completely describe the otolith transducer function between 0 and 1 G. In addition, a number of stimui can be generated by this device which are unique for the study of the semicircular canals.

The possibilities of this device should be further analyzed to determine design parameters for both animal rated and man rated versions. Beyond that, a prototype should be built, the characteristics analyzed, and control and operating techniques developed.

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